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Key Points:

- Geospatial analysis reveals a consistent relationship between elevation and open-water conversion in salt marshes
- The unvegetated-vegetated marsh ratio (UVVR) consistently indicates instability above a value of 0.1
- Marsh lifespan can be estimated by integrating elevation and the UVVR for current and potential rates of SLR

Supporting Information:

- Figure S1

Correspondence to:

N. K. Ganju,
nganju@usgs.gov

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Are Elevation and Open-Water Conversion of Salt Marshes Connected?

Neil K. Ganju¹ , Zafer Defne¹ , and Sergio Fagherazzi²

¹U.S. Geological Survey, Woods Hole Coastal and Marine Science Center, Woods Hole, MA, USA, ²Department of Earth Sciences, Boston University, Boston, MA, USA

Abstract Salt marsh assessments focus on vertical metrics such as accretion or lateral metrics such as open-water conversion, without exploration of how the dimensions are related. We exploited a novel geospatial data set to explore how elevation is related to the unvegetated-vegetated marsh ratio (UVVR), a lateral metric, across individual marsh “units” within four estuarine-marsh systems. We find that elevation scales consistently with the UVVR across systems, with lower elevation units demonstrating more open-water conversion and higher UVVRs. A normalized elevation-UVVR relationship converges across systems near the system-mean elevation and a UVVR of 0.1, a critical threshold identified by prior studies. This indicates that open-water conversion becomes a dominant lateral instability process at a relatively conservative elevation threshold. We then integrate the UVVR and elevation to yield lifespan estimates, which demonstrate that higher elevation marshes are more resilient to internal deterioration, with an order-of-magnitude longer lifespan than predicted for lower elevation marshes.

Plain Language Summary Salt marshes are valuable ecosystems that change in response to sea-level rise, sediment availability, storms, and other processes. Determining how salt marshes will change in the future is difficult. In this study we show that the elevation of a marsh relative to sea level is closely related to how much area it has been losing. The relationship between elevation and marsh area is the same across four large systems, and we can use these measurements to calculate how long a marsh will survive as sea-level rises. We found that the lowest marshes have a shorter lifespan than higher marshes, and these estimates can be used to help prioritize investments.

1. Introduction

Despite numerous investigations into salt marsh geomorphic trajectory, comprehensively assessing the status of salt marshes three-dimensionally is limited. Vertical investigations primarily focus on autochthonous and/or allochthonous sediment and organic matter sources for elevation change (Morris et al., 2002; Schile et al., 2014; Swanson et al., 2014), while lateral investigations focus on edge erosion (Leonardi et al., 2016) and open-water conversion (Mariotti, 2016). Linking the vertical and lateral status and trajectory of marshes is difficult, mainly due to incomplete geospatial coverage of critical parameters. In addition, it is conceptually difficult to reconcile the two dimensions when invoking marsh evolution mechanisms. The separation between vertical and lateral process-based research has hampered holistic thinking on marsh vulnerability because it reinforces incomplete models of landscape evolution (Ganju, 2019).

Connecting the lateral and vertical dimensions requires geospatial data sets that quantify appropriate metrics across entire systems. Observational data are typically collected at discrete points, which cannot capture the full distribution of states (i.e., marsh plain, channels, flats, and ponds). Defne et al. (2020), following the methods of Ganju et al. (2017), developed a “marsh unit” concept, that uses continuous elevation data across a marsh system to delineate individual parcels. From a geospatial perspective, the delineation integrates the marsh platform between large tidal creeks and upland ridges, while from a management perspective, it offers a parcel-based approach that aids in decision making. Once marsh units are delineated, computing metrics over the defined area is straightforward and enables comparisons between units, investigation of system gradients, and analysis of cross-system behaviors. Ganju et al. (2017) also introduced the unvegetated-vegetated marsh ratio (UVVR), a spatially integrated metric that they correlated with the net sediment budget and ultimately trajectory of microtidal marshes. In that study, seasonal-to-annual sediment fluxes were compared with the remotely sensed UVVR as an independent stability metric, and though a

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causal link was not implied, the implication was that various destructive forces (herbivory, salinity stress, sea-level rise) simultaneously increased the UVVR and sediment liberation from the marsh systems studied.

Here we use the marsh unit and UVVR framework to test the following hypotheses: (i) vertical position and lateral instability are intrinsically related; (ii) the relationship between the two may be generalizable across salt marsh systems; and (iii) the metrics can be integrated to evaluate lifespan based on available sediment capital (Cahoon et al., 2019). We first examine four estuarine-salt marsh systems to test these hypotheses, then describe the marsh unit delineation, calculation of metrics, and application of future scenarios to estimate marsh unit lifespans. We then report relationships between marsh unit elevation and the UVVR, how the relationship varies across systems, and to what degree lifespans change under global mean sea-level rise scenarios (Sweet et al., 2017). Finally, we speculate on the mechanisms leading to these relationships, implications for geomorphic evolution, and application of these concepts for rapid assessment of marsh vulnerability to sea-level rise and open-water conversion.

2. Methods

2.1. Site Descriptions

We conducted geospatial analyses in four estuarine-salt marsh systems on the northeast U.S. Atlantic coast: Chincoteague Bay, Maryland/Virginia; Great South Bay, New York; Cape Cod National Seashore, Massachusetts; and Plum Island Estuary, Massachusetts.

Chincoteague Bay straddles the eastern coast of the Delmarva peninsula, and is bordered by Assateague Island National Seashore and Chincoteague National Wildlife Refuge on the east, and the mainland peninsula on the west. Two inlets at the north and south control exchange with the Atlantic Ocean. Tidal range varies from 1.1 m in the inlets to a minimum of less than 0.1 m in the central bay (Beudin et al., 2017). The overall marsh area considered for this analysis is 112 km². Salt marshes in this system span a range of geomorphic environments, including the back-barrier, flood-tidal shoals, and estuarine fringe.

Great South Bay is the largest subembayment of a series of connected estuaries on the south shore of Long Island, New York, bordered by Fire Island National Seashore on the south and mainland on the north. The estuary is connected to the Atlantic Ocean via Fire Island Inlet, Wilderness Inlet, and to other subembayments on the eastern and western boundaries. Tidal range varies from 1 m in the inlets to a minimum of 0.3 m in the central bay (Aretxabaleta et al., 2017). The overall marsh area considered for this analysis is 29 km². The majority of salt marshes in this system are on the landward side of the barrier island, with the remainder fringing the mainland.

The salt marshes of Cape Cod National Seashore are scattered through several individual estuarine systems that are not hydrologically connected; some are on the open Atlantic Ocean Coast, while others are within Cape Cod Bay. Tidal range varies from a maximum of 3 m near the marshes at the entrance to Cape Cod Bay and a minimum of 1.2 m along the southernmost marshes (Defne & Ganju, 2019). The overall marsh area considered in this system is 16 km².

The Plum Island Estuary contains 49 km² of marsh area, along the periphery of the estuary and landward along several tidal rivers. Tidal range within the estuary is a maximum of 2.7 m near the mouth of Plum Island Sound, and a minimum of 2.3 m near the landward extent of the system up the Merrimack River (Defne & Ganju, 2018a). The marshes vary in morphology from back-barrier parcels to extensive riverine marshes along tidal tributaries.

2.2. Geospatial Analysis and Associated Methods

2.2.1. Elevation and Marsh Unit Delineation

Elevation was extracted at 1-m horizontal resolution from the Coastal National Elevation Database (CoNED; Danielson et al., 2016). The CoNED (<https://www.usgs.gov/land-resources/eros/coned>) utilizes multiple topo-bathymetric data sources to create a seamless elevation data product that can represent subtidal and subaerial features. Assessing elevation metrics across regional scales at marsh unit resolution requires a consistent data product such as the CoNED, as intensive real-time kinematic GPS surveys are impractical over these spatial scales. In salt marsh areas, bare-earth lidar signals can be biased due to interference from the vegetative canopy, and correction methods based on vegetation density and selected ground-truthing points have been suggested (Buffington et al., 2016). Over the spatial scales

considered here however, corrections based on vegetation density may add additional uncertainty unless a comprehensive field survey was undertaken across the entire system. Given the aggregation of these data over marsh units, the underlying elevational trends across large expanses should dominate the signal. Elevation was corrected to local mean sea level using VDatum to enable cross-system comparisons.

For each salt marsh complex, the upland and open-water boundaries were based on the National Wetland Inventory's classification of estuarine intertidal wetlands (Defne & Ganju, 2018b). The elevation data were used to delineate the marsh into hydrologically connected units using GIS analysis (Ganju et al., 2017). Flow accumulation based on the relative elevation of each location was used to determine the ridge lines that separate each marsh unit, while the surface slope was used to automatically assign each unit a drainage point, where water is expected to drain through. Units with a surface area smaller than 5,000 m² were merged with adjacent units. Creeks narrower than 10 m and internal ponds were integrated into marsh units.

2.2.2. UVVR

The UVVR was determined using 1-m horizontal resolution aerial imagery from the National Agricultural Imagery Program (NAIP) and 1-m horizontal resolution CoNED elevation data, with the Marsh Edge from Image Processing method (Farris et al., 2019). Briefly, four bands (red, green, blue, near infrared) from 8-bit NAIP imagery and the elevation data set were grouped into 32 classes with unsupervised classification (minimum class size of 5,000 cells). These classified data were then reclassified to vegetated and unvegetated areas by visual comparison with the visible spectrum NAIP imagery (red, green, blue bands). The unvegetated and vegetated pixels were then aggregated across marsh units to provide areas; the UVVR is the ratio of unvegetated to vegetated area (i.e., varies between 0 and infinity; see below for discussion on nominal limits to the UVVR).

2.2.3. Tidal Range

Mean tidal range was based on the calculated difference in height between mean high water and mean low water using the VDatum (v3.5) database (<http://vdatum.noaa.gov/>). In some cases, VDatum data quality is limited at the landward ends of these estuarine domains; therefore, we only investigated the system-mean values as a diagnostic variable.

2.2.4. Sediment-Based Lifespan and Sea-Level Rise

Ganju et al. (2017) presented a methodology to compute the sediment-based lifespan of an entire marsh complex using the sediment budget, UVVR, elevation of the vegetated plain, and local relative sea-level rise. The net sediment budget of a marsh system, Q_b , is defined as

$$Q_b = Q_s - \rho_{min} \times SLR_{local}, \quad (1)$$

where Q_s is the measured annual sediment flux (kg m⁻² year⁻¹), ρ_{min} is the representative minimum dry bulk density required to keep up with sea-level rise (159 kg m⁻³ following Morris et al., 2016, and Ganju et al., 2017), and SLR_{local} is the local relative sea-level rise rate (m year⁻¹). Equation (1) represents a current sediment budget that consists of the measured flux to the marsh complex per unit area, less the sediment accretion required to keep pace with sea-level rise. The relatively low density value is used to give the most conservative estimate of sediment required. The relationship between Q_b and UVVR presented by Ganju et al. (2017; supporting information Figure S1) is approximated here by the equation

$$Q_b = -0.42 \log UVVR - 1.08, \quad (2)$$

Note that at a UVVR ~0.08, the sediment budget is predicted to be neutral. The total available sediment mass in the vegetated marsh plain, M_{sed} , is approximated as

$$M_{sed} = E_m \times A_{veg} \times \rho_{mean}, \quad (3)$$

where E_m is the mean elevation above mean sea level of the vegetated marsh plain within each marsh unit, A_{veg} is the vegetated area within the unit, and ρ_{mean} is a representative mean dry bulk density of the sediment stored within the marsh plain (373 kg m⁻³ following Morris et al., 2016, and Ganju et al., 2017). Next, the sediment-based lifespan of the marsh system, L_{sed} , is calculated as

$$L_{sed} = -M_{sed} / (Q_b \times A), \quad (4)$$

where A is the total area of the marsh unit (i.e., sediment is assumed to be extracted from the entire system, not only the vegetated plain). The negative sign is required to convert the sediment export (negative) to a positive lifespan (units with a positive sediment import have an undefined lifespan). This calculation is performed for each marsh unit to yield a distribution of lifespans across each system.

We then estimate marsh unit lifespans under future global mean sea-level (Sweet et al., 2017) by modifying SLR_{local} for three scenarios: 0.3, 0.5, and 1.0 m of rise by 2100, recast as annual rates. These scenarios are downscaled by Sweet et al. (2017) to local sites along the U.S. coast (Table S1); here we have chosen the most likely scenario (fiftieth percentile of climate-driven sea-level rise scenarios). The background sea-level rise due to nonclimatic processes (Sweet et al., 2017) is subtracted from these values in equation (1) to yield an excess sediment deficit under increasing global mean sea-level rise rates. The lifespan is then recomputed, providing an estimate of present-day lifespan under future sea-level rise scenarios.

3. Results

3.1. Marsh Unit and Elevation Characteristics

The marsh unit delineation resulted in a variable number of units for each system (e.g., 500 for Cape Cod and 3,300 for Chincoteague Bay), with the average area of units remaining relatively similar (~26,000–41,000 m² across all sites). Mean system-wide elevations were 0.33 (Chincoteague Bay), 0.41 (Great South Bay), 0.85 (Cape Cod), and 1.27 m (Plum Island Estuary), with elevation among systems increasing along a south-north gradient (Figure 1; Table S2). Within systems, clear elevational gradients were observed; for example, in Chincoteague Bay, the elevation of back-barrier marshes increased moving eastward toward the crest of the barrier island. In the Plum Island Estuary, the lowest elevations were found on estuary-fringing marshes closest to the open-water expanse of Plum Island Sound, whereas the highest elevation marshes were further landward along tidal rivers. Tidal range also increased along a south-north latitudinal gradient (Table S2), with a range from 0.4 (Chincoteague Bay) to 2.65 m (Plum Island Estuary).

3.2. Distributions of UVVR

The UVVR (Figure 1) varied from the minimum possible value of 0 (i.e., no open water, completely vegetated) to maximum values exceeding 100 (i.e., <1% vegetated). Conceptually, a marsh unit with a UVVR greater than 2 (i.e., 67% unvegetated) is functioning as an intertidal flat or estuarine embayment, and we therefore restrict our ensuing analyses to marsh units with UVVR <2 and/or elevation above mean sea level. This excludes 8% of marsh units at Chincoteague Bay, and 3% or less of marsh units in the other systems. Every system had at least 50% of marsh units with a UVVR above 0.08 (i.e., above 7.4% unvegetated area), which is the sediment-neutral tipping point predicted by equation (2) (Table S2). There was a trend of decreasing UVVR with higher mean elevation and mean tidal range across systems, suggesting an intrinsic relationship between the variables (median UVVR ranging from 0.1 to 0.2, Plum Island, Cape Cod, Great South Bay, and Chincoteague Bay, respectively).

A negative correlation between UVVR and elevation within each marsh system was indicated by linear regression of the log-transformed variables (Figure 2a), though there was substantial scatter within a system. Nonetheless, bin-averaging by elevation confirmed a general trend of decreasing UVVR with increasing elevation that was observed at all systems (Figure 2b). Linear regression between log-transformed elevation and bin-median UVVR yielded determination coefficients (R^2) between 0.57 (Great South Bay) and 0.85 (Chincoteague Bay).

The dependence of the UVVR-elevation relationship on tidal range and/or mean system elevation is apparent, with similar relationships for Chincoteague and Great South Bays (mean tidal range ~0.4 m), and a shift to higher elevation for a given UVVR in Cape Cod and Plum Island Estuary (mean tidal range >2 m). Therefore, we normalized marsh unit elevation by subtracting the system-wide mean marsh elevation, and subsequently dividing by system-wide mean tidal range. This procedure significantly changed the linear regression of log-transformed quantities (Figures 2c and 2d), leading to dissimilar behaviors at the lower and upper limits of elevation. In fact, the higher tidal range systems (Plum

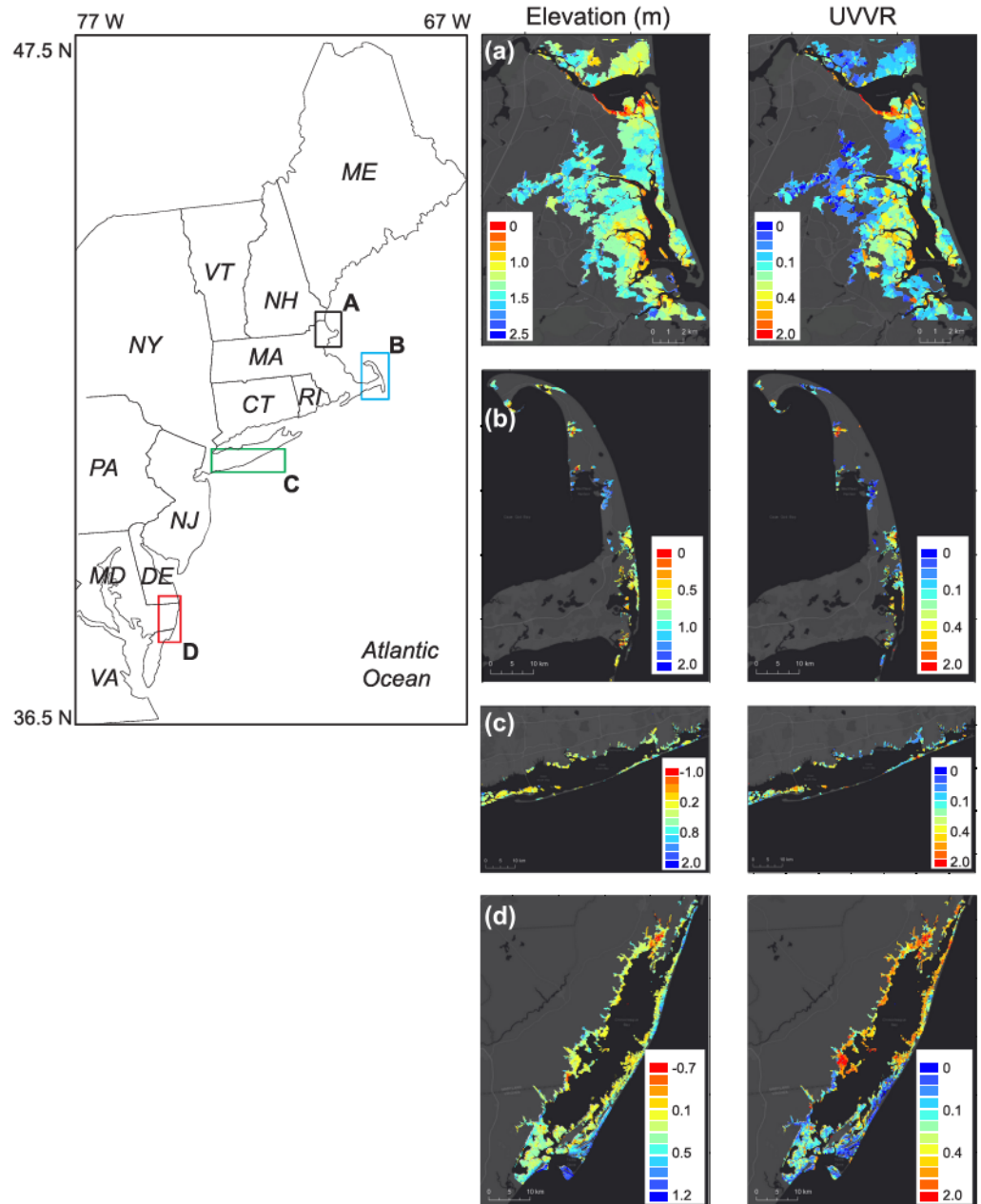


Figure 1. Study locations on the northeastern coast of the United States; (a) Plum Island Estuary, Massachusetts; (b) Cape Cod National Seashore, Massachusetts; (c) Great South Bay, New York; and (d) Chincoteague Bay, Maryland/Virginia. Left panels are marsh unit elevation in meters (NAVD88), right panels are the unvegetated-vegetated marsh ratio (UVVR).

Island and Cape Cod) exhibited a larger slope in the normalized elevation-UVVR relationship (i.e., relatively lower UVVR at high normalized elevations, and relatively higher UVVR at low normalized elevations; Figure 2c). This indicates more extreme conditions of resilience and vulnerability along the elevation spectrum, which may be related to the stronger hydrodynamic forcing in large tide range systems. However, around the mean normalized elevation (i.e., a value of zero in Figures 2c and 2d), there was a strong convergence near a UVVR of approximately 0.1 (Figure 2e), slightly above the sediment-neutral UVVR of 0.08. This indicates that across these systems, units at elevations above the mean normalized elevation are laterally intact, while units at elevations below the mean normalized elevation are potentially crossing a lateral stability threshold.

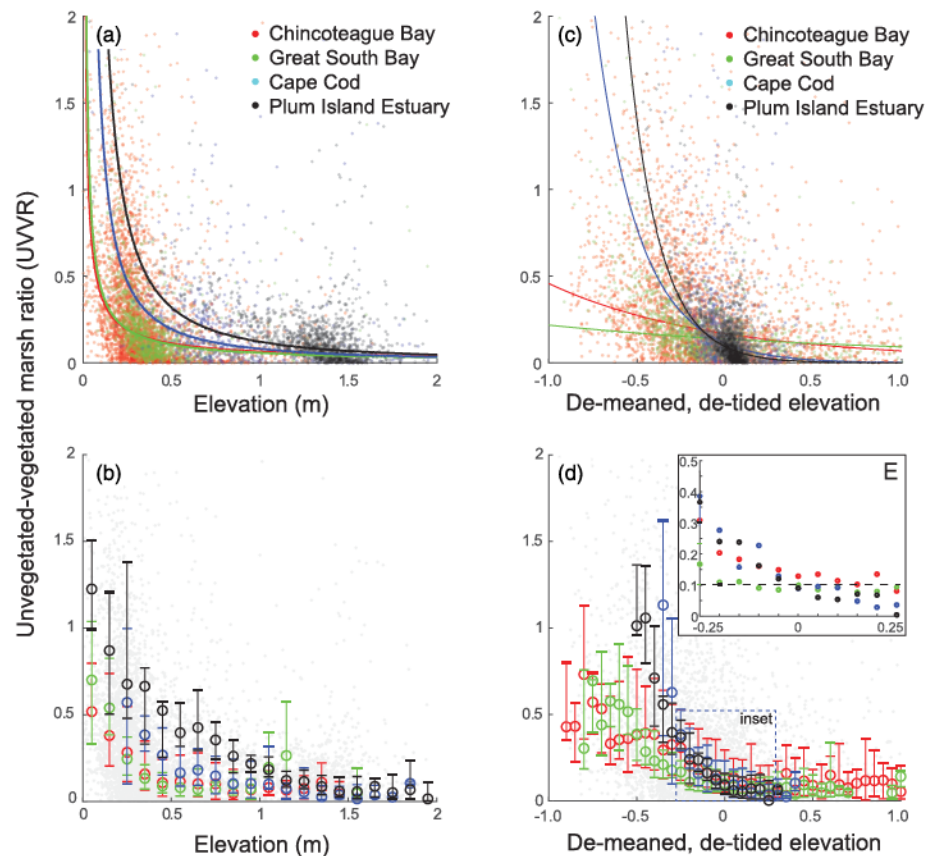


Figure 2. Relationships between (a) marsh unit elevation and UVVR; (b) bin-averaged marsh unit elevation and UVVR with 25% and 75% quantiles indicated by bars; (c) demeaned and detided marsh unit elevation and UVVR; (d) bin-averaged demeaned and detided marsh unit elevation and UVVR with 25% and 75% quantiles indicated by bars; and (e) inset of (d) to demonstrate crossing of UVVR = 0.1 threshold near a normalized elevation of 0 (i.e., mean marsh unit elevation with respect to individual marsh system).

3.3. Present and Future Lifespan Distributions

Present-day lifespan distributions (Figure 3) show a strong trend of increasing lifespan with lower UVVR, with scatter within and across systems resulting from differences in elevation and therefore expected sediment capital (Cahoon et al., 2019). For example, at a UVVR of 1 ± 0.02 (i.e., 50% vegetated), the average difference in lifespan between units in the lowest elevation system (Chincoteague Bay) and the highest elevation system (Plum Island Estuary) is over threefold (from 60 to 180 years), highlighting the value of elevation and sediment capital to resilience. At the nominal upper limit of UVVR = 2, the range of lifespans is between 15 and 65 years. Median lifespans under present-day conditions (Figure 4) track both the median UVVR and elevation trends, with the shortest median lifespan of 160 years in Chincoteague Bay, and the longest median lifespan of 1,100 years in the Plum Island Estuary.

We then developed future lifespan estimates of each marsh unit using downscaled sea-level rise predictions (Figure 4), and found that marsh units within the lowest elevation system (Chincoteague Bay) have a median lifespan of ~50 years under a 1.0-m global mean sea-level rise scenario. The highest elevation system (Plum Island Estuary) had a median marsh unit lifespan of ~230 years under a 1.0-m global mean sea-level rise scenario. Under less drastic sea-level rise, the median lifespans in Chincoteague Bay are still 100 years or less, indicating imminent (and ongoing) marsh loss in low-elevation, back-barrier marshes.

Within systems, there are significant spatial gradients in UVVR and elevation that influence lifespan, though the underlying UVVR-elevation relationship is consistent. For example, in Chincoteague Bay, marsh units on the landward side of the barrier island have higher elevations and lower UVVRs on average as compared to mainland marsh units (0.40 vs. 0.28 m, and UVVR = 0.36 vs. 0.75, respectively). The mechanism for

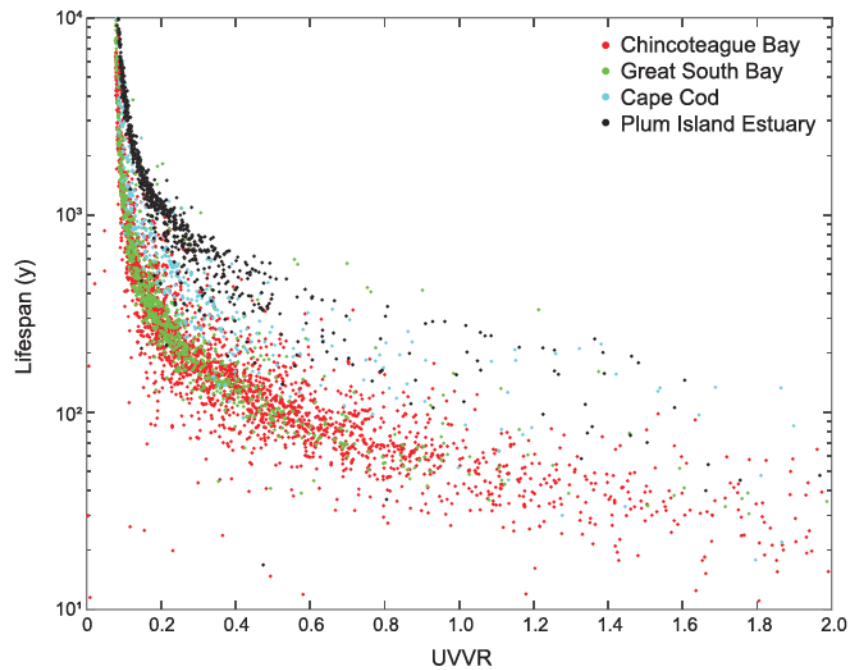


Figure 3. Relationship between marsh unit UVVR and sediment-based lifespan, across four salt marsh systems. Difference in lifespan for a given UVVR is a function of marsh unit elevation, with increasing elevation resulting in higher sediment capital and prolonged lifespan.

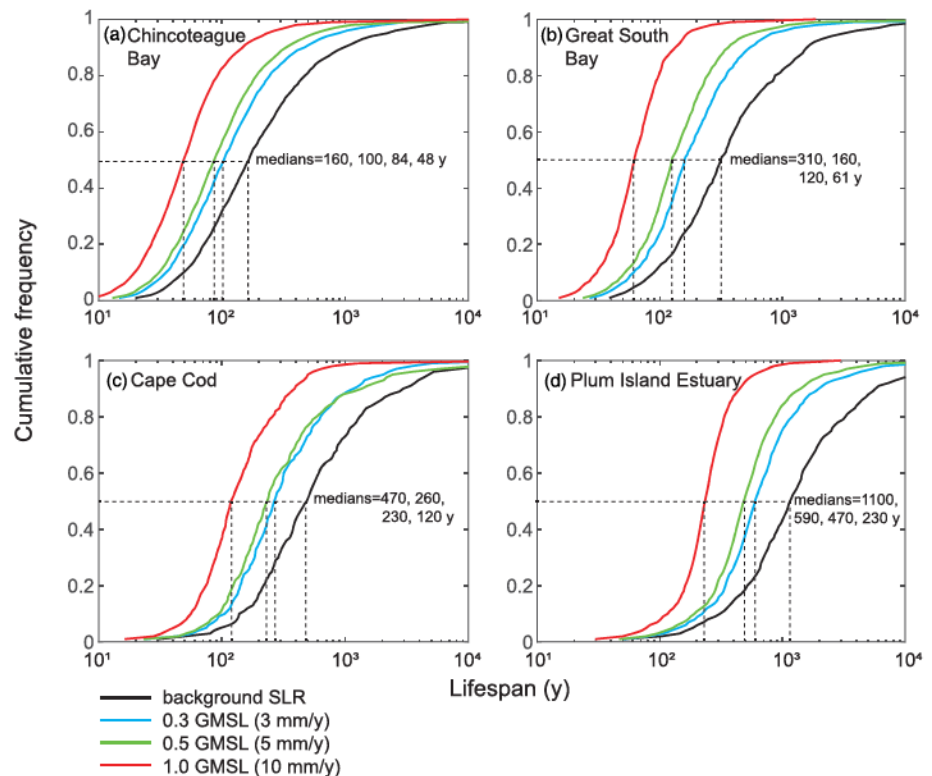


Figure 4. Median lifespans across four marsh systems; (a) Chincoteague Bay, (b) Great South Bay, (c) Cape Cod, and (d) Plum Island Estuary, for current sea-level rise rates and three future global mean sea level (GMSL) scenarios, downscaled to local sites by Sweet et al. (2017).

this pattern is not clear, but appears to match the barrier island rollover concept, as marshes with potential for overwash have more resilience via increased sediment supply and elevation as compared to estuarine mainland marshes with limited sediment input (Walters et al., 2014). In the Plum Island Estuary, there is a general trend of increasing elevation, decreasing UVVR, and increasing lifespan in the landward direction, both along tidal rivers and from the estuarine shore-marsh plain direction. This pattern fits a general marsh transgression conceptual model as described below, with seaward marsh areas more susceptible to degradation and marsh plain loss. Patterns in Great South Bay and Cape Cod were not readily discernable, given the distance between marsh units and more complex geomorphic setting (i.e., spatial variations in hydrodynamic forcing and proximity to developed areas, respectively).

4. Discussion

4.1. Identifying Thresholds With the UVVR

The apparent coherence of the normalized elevation-UVVR relationship across these four systems suggests a connection between vertical position and exposure to forces of deterioration (discussed below), but furthermore, the convergence near a UVVR of 0.1 matches three prior, independent studies. The coupled biogeomorphic modeling of D'Alpaos and Marani (2016) implemented sea-level rise and sediment supply scenarios for a realistic marsh-channel system, and showed establishment of a stable system under the highest sediment load, lowest sea-level rise scenario. That set of simulations was reinterpreted in a UVVR context by Ganju et al. (2017), with the most stable scenario approaching a UVVR = 0.13. The sediment budget analysis detailed by Ganju et al. (2017) identified the crossing from a positive to a negative sediment budget at a UVVR = 0.1. Most recently, Wasson et al. (2019) compared pairs of stable and deteriorating marshes, and showed that the decadal change in UVVR increases at a UVVR >0.15, with stable UVVR (i.e., minimal decadal change and no open-water conversion) below this threshold. This convergence of threshold indicators shows that monitoring of the UVVR over multiple spatial and temporal scales can lend insight not only to the mechanistic processes controlling marsh trajectory, but for guiding management and restoration priorities.

4.2. Marshes in a Transgressive Landscape

The correlation between elevation and the UVVR is most readily explained by the development of marshes along a preexisting transgressive coastal landscape (FitzGerald et al., 2018). In the initial response to sea-level rise, hydrodynamic processes extract sediment from the back-barrier system to compensate for increased depth (i.e., accommodation space). This “cannibalization,” whether from tidal creek scour or marsh edge erosion, will ultimately lead to marsh platform loss through slumping or opening of edge ponds that may rapidly convert to open estuary (Mariotti, 2016). Additionally, the deterioration at lower elevation marsh units is likely an outcome of coupled bio-physical processes, including vegetation mortality near high-disturbance areas (Elsley-Quirk et al., 2019), susceptibility of relatively lower marshes to increased wrack deposition (Tolley & Christian, 1999), and interactions between flooding frequency and disturbance recovery (Smith et al., 2012). It is intuitive that lower elevation marshes, with their proximity to tidal forcing and inundation, are more susceptible to ponding, which can ultimately induce vegetation loss and open-water conversion. From a geomorphic perspective, the presence of intertidal flats (not colonized by vegetation due to insufficient sediment supply) on the seaward edges of marsh units also contributes to increased UVVR near the estuary-marsh boundary.

The relative location of the marsh unit with respect to a sediment source or sink also determines marsh resilience to sea-level rise (Ganju et al., 2013). In a sediment-poor system, lower marshes along the estuarine border will tend to export sediment to the estuary over the long term through transport out of tidal channels, via dispersive flux (i.e., higher sediment concentrations on ebb tide; Nowacki & Ganju, 2019). Conversely, in a sediment-rich system, marshes tend to build on expanding intertidal flats or high elevation levees closer to the sediment source, and the seaward progradation of the marsh edge may generate a less obvious relationship between elevation and the UVVR. In unvegetated areas with restored tidal connectivity and a large external sediment supply such as polders (Brunetta et al., 2019), the UVVR will likely decrease from infinity to a stable value as sediment is imported and elevation increases, but the temporal evolution of that relationship has yet to be investigated.

4.3. Formalization of Marsh Unit Delineation, Application, and Forecasting

Salt marsh parameters are typically assessed using on-the-ground methods such as surface elevation tables, real-time kinematic GPS surveys, and/or vegetation transects across vegetated portions of the plain. While valuable for their accuracy and characterization of the elevational state, these methods are difficult to standardize for wide spatial application within a given estuary-marsh system or across systems. The inherent value of the marsh unit delineation and computation of standardized metrics is most obvious from an assessment perspective. Practitioners devote significant effort and time toward developing assessment protocols, but this study shows that two straightforward geomorphic metrics are inherently linked across large spatial scales. The implication is that across an entire marsh landscape, we can assess which marsh units are most susceptible to vertical submergence and open-water conversion by monitoring the UVVR over multiple timescales and resolutions. Additionally, forecasting using the lifespan method may be preferable to deterministic modeling, as the input variables (UVVR and elevation) can be updated regularly with imagery and lidar surveys, over previously delineated marsh units. The efficacy of the lifespan concept (and thresholds noted above) can therefore be tested: marsh units with predicted short lifespans should see a consistent increase in UVVR and/or decrease in elevation that exceeds marsh units with longer lifespans. Conversely, potential benefits of management actions should be measurable as UVVR decreases in response to restoration. Lastly, these data should be considered fundamental for model assessment: can marsh evolution models recreate these underlying relationships, thresholds, and coupled vertical-lateral trajectories?

5. Conclusions

Salt marsh vulnerability to sea-level rise, sediment deficits, and internal disturbances is of widespread interest; however, robust assessment methods that consider the three-dimensionality of marshes are rare. The spatial scale of salt marsh complexes necessitates geospatial analyses that consider all three dimensions, and here we integrate the vertical dimension (through marsh elevation) with the lateral dimensions (through the UVVR) to shed light on the relationship between vertical and horizontal marsh dynamics across four northeastern U.S. systems. A consistent relationship between the UVVR and elevation is congruent with the concept of marsh transgression, as lower elevation marshes are more susceptible to laterally destructive forces on the seaward edge. Furthermore, the sediment capital within a marsh, represented by elevation, and the lateral instability, represented by the UVVR, can be combined to yield lifespan estimates that may be formalized and updated with repeated surveys. These techniques aid in understanding the underlying mechanism of geomorphic evolution in back-barrier marsh systems, and help guide restoration and management efforts.

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